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A DESIGN FOR PROJECT BRONCO, AN EXPERIMENT FOR NUCLEAR FRACTURING AND IN SITU RETORTING OF OIL SHALE

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CONTENTS

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ABSTRACT

This report describes Project Bronco, a proposed 50-kiloton nuclear explosion experiment. The detonation will fragment and fracture a deep, thick oil shale deposit which will subsequently be retorted in place. Bronco will provide information related to: the technical and economic feasibility of the basic concept, a predictive capability for the physical effects of nuclear explosions, and the distribution of radioactivity and its behavior during retorting.

Although the Bronco experimental design is based on a particular site in the Piceance Creek Basin, a preshot investigation will determine whether the nominated site will meet the technical and safety criteria for a first nuclear explosion in oil shale.

Following site confirmation, holes will be drilled for fracture studies, for emplacing the explosive, and for shock wave measurements. The explosion is expected to produce a chimney 230 ft across and 520 ft high (measured up from the shot point), containing over one million tons of fragmented oil shale. Fractures may extend as far as 460 ft laterally beyond the chimney edge. Postshot drilling will reveal the size and shape of the chimney, the extent of fracturing, and the distribution of heat and radioactivity.

The final design of the in situ retorting experiment will depend on results of the postshot exploration and on laboratory research currently underway. Tentatively, mixtures of air and recycle gas will be injected via drill holes to the chimney top. Drill holes to the chimney bottom will remove off-gas, oil mist, and liquid oil. During retorting, measurements will be made of temperatures in the chimney. Samples of gas and oil will be analyzed for physical characteristics, chemical composition, and radioactive content, if any. Additional data on retorting efficiency will be obtained in post-retorting drill holes.

It is tentatively planned to follow the chimney retorting with an experimental outward-moving burn in a 45° sector of the fractured region outside the nuclear chimney.

INTRODUCTION

Since 1958, the concept of using underground nuclear explosions to assist in the recovery of oil from oil shale deposits has been under joint study by the U. S. Bureau of Mines (BuMines), the U. S. Atomic Energy Commission (AEC), and an AEC technical contractor, the Lawrence Radiation Laboratory at Livermore (LRL). Papers on the subject were presented at a 1958 government-industry meeting in Dallas and at the Second Plowshare Symposium in May 1959 in San Francisco.[1] In 1960, BuMines, AEC and LRL cooperated in the conduct of an experiment involving the detonation of a high-explosive charge in oil shale at the Bureau's Anvil Points, Colorado, mine.[2]

Further developments of the idea, reflecting advances in the technology of underground nuclear explosions and an increased knowledge of the extent and nature of U. S. oil shale resources, has led to several published papers by AEC, BuMines, and LRL personnel.[3,4,5] Growing industrial interest in the process was evidenced in a 1966 paper by Coffer and Spiess.[6] Shortly thereafter, CER Geonuclear Corporation (CER) formed a group of industrial corporations, mainly oil interests, to support a nuclear explosion experiment in oil shale. Further technical work, both theoretical and experimental, has been done on the in situ retorting of oil shale fragmented by underground nuclear explosions.[7]

Beginning in 1965, BuMines and AEC embarked on a cooperative program of geologic explorations to aid in the search for a site for a nuclear explosion experiment in oil shale. The BuMines/AEC Colorado Core Hole No. 1 (CCH #1) was drilled on Yellow Creek in northern Piceance Creek Basin. In 1966, BuMines/AEC CCH #2 was drilled at Duck Creek, 10 miles to the southeast. Information gathered in this program substantially increased earlier estimates of the thickness and extent of oil shale deposits in this region.[8] Unexpected underground water was encountered in both holes. In each, however, thick sections of dry oil shale were identified. The exploration also showed that the heavy deposits of halite associated with the occurrence of oil shale in the central part of the Basin do not extend to the north. Figure 1 is a map of the area.

A feasibility study conducted by BuMines, AEC and CER in 1967 concludes that the recovery of oil from oil shale deposits broken by nuclear explosions may become an economically attractive industrial process.[9] The report also states that a nuclear explosion experiment is needed to assess the technical and economic feasibility of the concept.

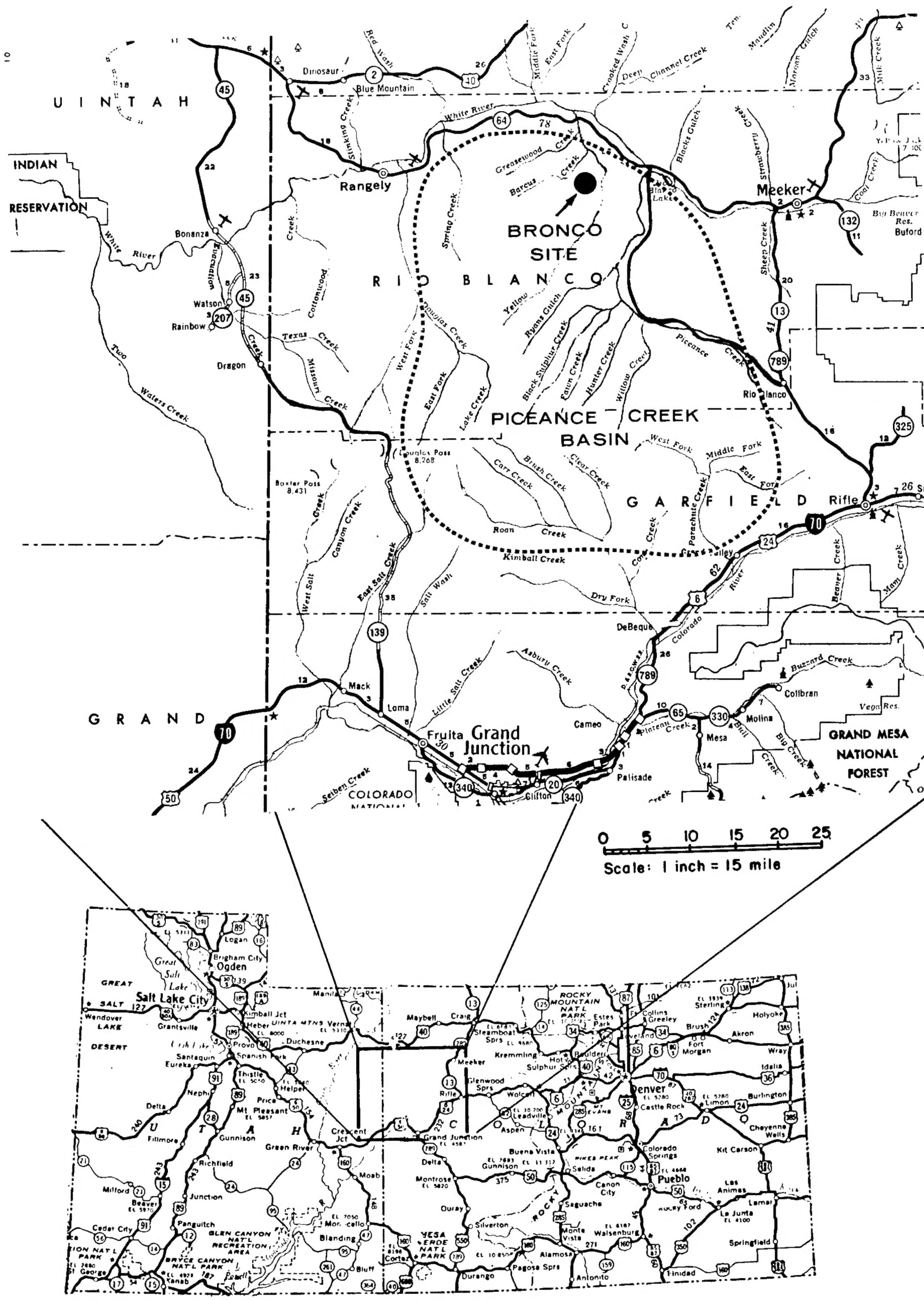


Fig. 1. Regional map, Piceance Creek Basin, showing the location of the proposed Bronco site.

OBJECTIVES

Project Bronco has been designed to provide answers to several fundamental technical questions related to the recovery of oil from oil shale broken by underground nuclear explosions. The basic objectives of the experiment are:

1. To assess the technical and economic feasibility of in situ retorting as a method for recovering oil from oil shale fragmented and fractured by an underground nuclear explosion.
2. To confirm and refine the capability to predict physical properties and geometry of the cavity, the chimney, and the fractured region produced by a nuclear explosion in oil shale.
3. To investigate the form and distribution of radioactivities left by the detonation and to assess their behavior during in situ retorting.

This experimental plan does not include detailed safety and security programs, detailed nuclear engineering design, or specific engineering details for measurement and control of retorting processes. It does include the major construction and equipment items and a description of the experimental program.

The design for the postshot retorting phases is as complete as technical information will allow, but is not yet well enough defined to assure that the first objective can be attained. As further research data become available, the experimental plan will be refined. A final design can be achieved only when results of the postshot exploration have been analyzed.

However, knowledge gained of the fracturing and other effects of the explosion is expected to be of significant value to several potential nuclear explosion applications, independent of the design of the chimney treatment experiment.

SITE CHARACTERISTICS AND EXPLOSION EFFECTS

A committee of representatives from LRL-Livermore and various agencies of the U. S. Department of the Interior, including BuMines, has drawn up a set of technical criteria for a site for a nuclear oil shale experiment.[10] Suggestions from CER[11] and other interested parties proved helpful in the committee's deliberations. The technical criteria include: restrictions on overburden and on oil shale thickness, grade and uniformity; restrictions on the proximity and deliverability of aquifers; restrictions on faults, fracturing, and surface zero topography and on requirements for remoteness.

PROPOSED SITE

A subsequent search of U. S. oil shale deposits revealed a location near the S. E. corner of Section 15, T 1 N, R98W, Rio Blanco County, Colorado, which appears, on the basis of available data, to satisfy the requirements. Figure 2 is an aerial photograph of the general site area and identifies Colorado Core Hole No. 1 (CCH #1). Figure 3, an enlargement of a portion of Fig. 2, shows tentative locations of Project Bronco drill holes.

The recommended area lies about 1-3/4 miles west of Core Hole No. 1. A major topographic feature of the area is a locally prominent peak. A high, gently sloping plateau to the south and southwest of this peak appears to be well-suited for the proposed operation. The elevation of the plateau is about 6400 ft above sea level. The flat region is irregular in shape, and about 1500-2500 ft across. The plateau surface is slightly rolling, with a local relief of 20-30 ft. A few erosional streambeds which follow regional fracture patterns cut the plateau surface, but not deeply. Vegetation consists mainly of scrub cedar and sage, rooted in a thin layer of coarse soil. Approximately 1.5 miles of road construction will be necessary to provide access to the site.

Although the general area is used as cattle range in the summer, there are no

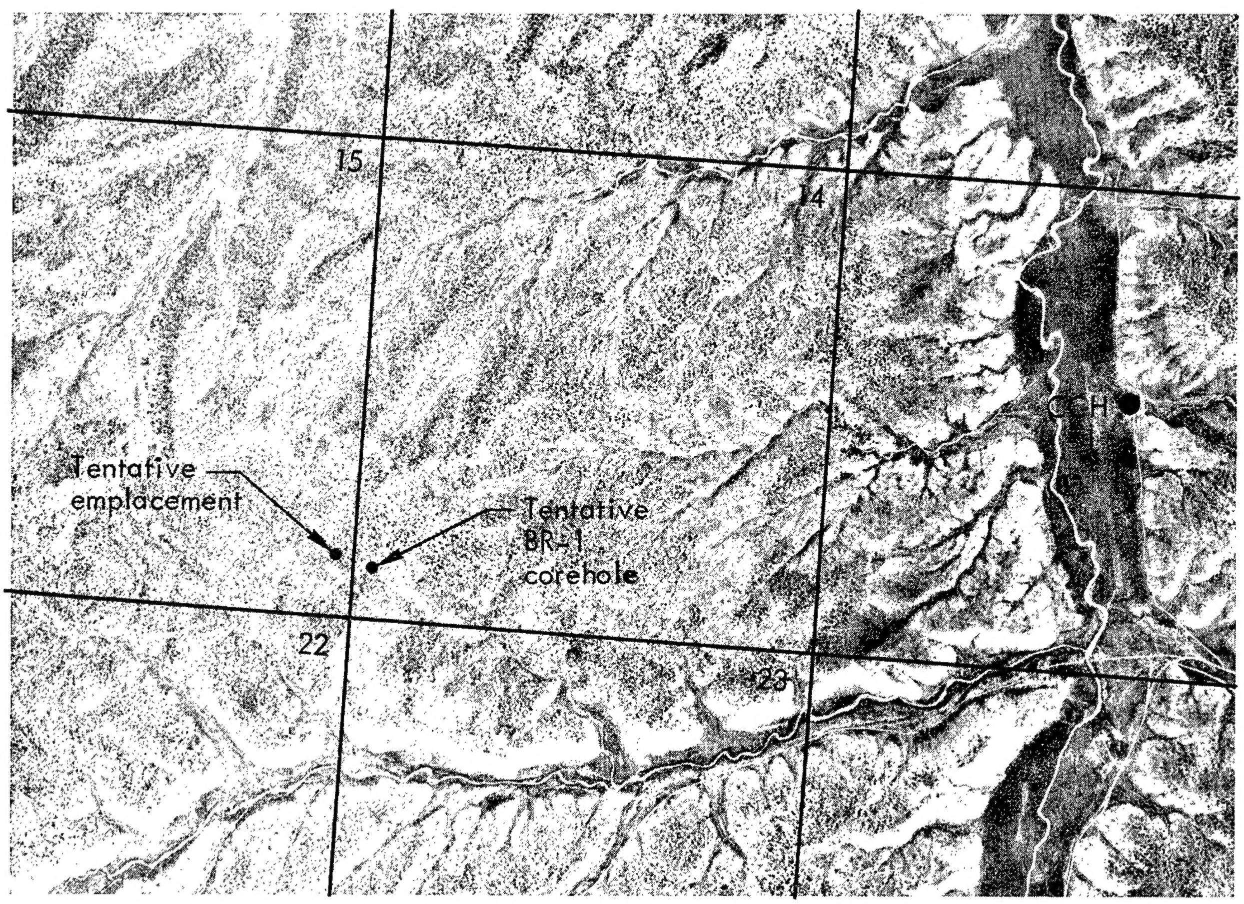


Fig. 2. General Broncho site area, part of T1N, R98W, Colorado.

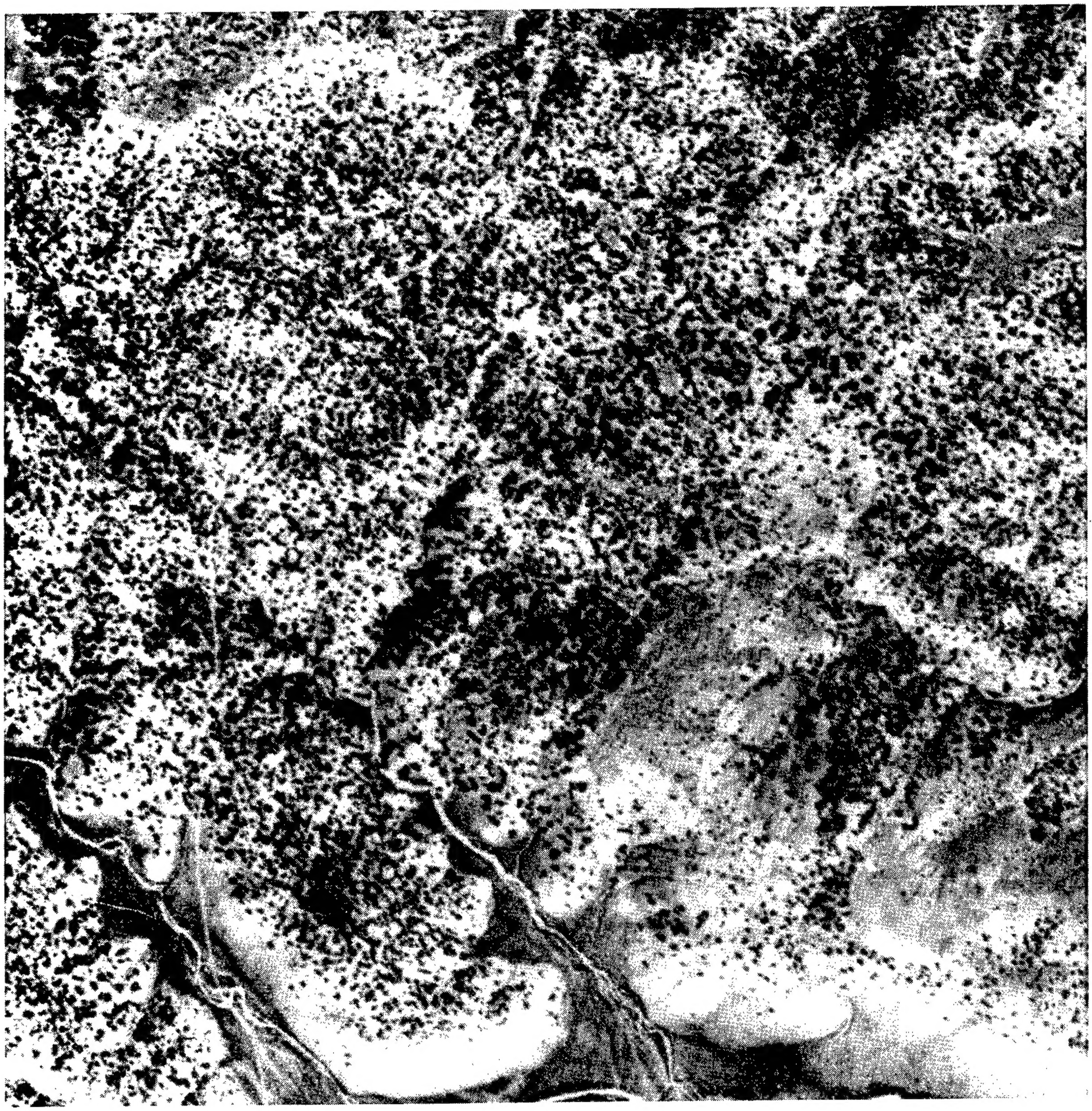
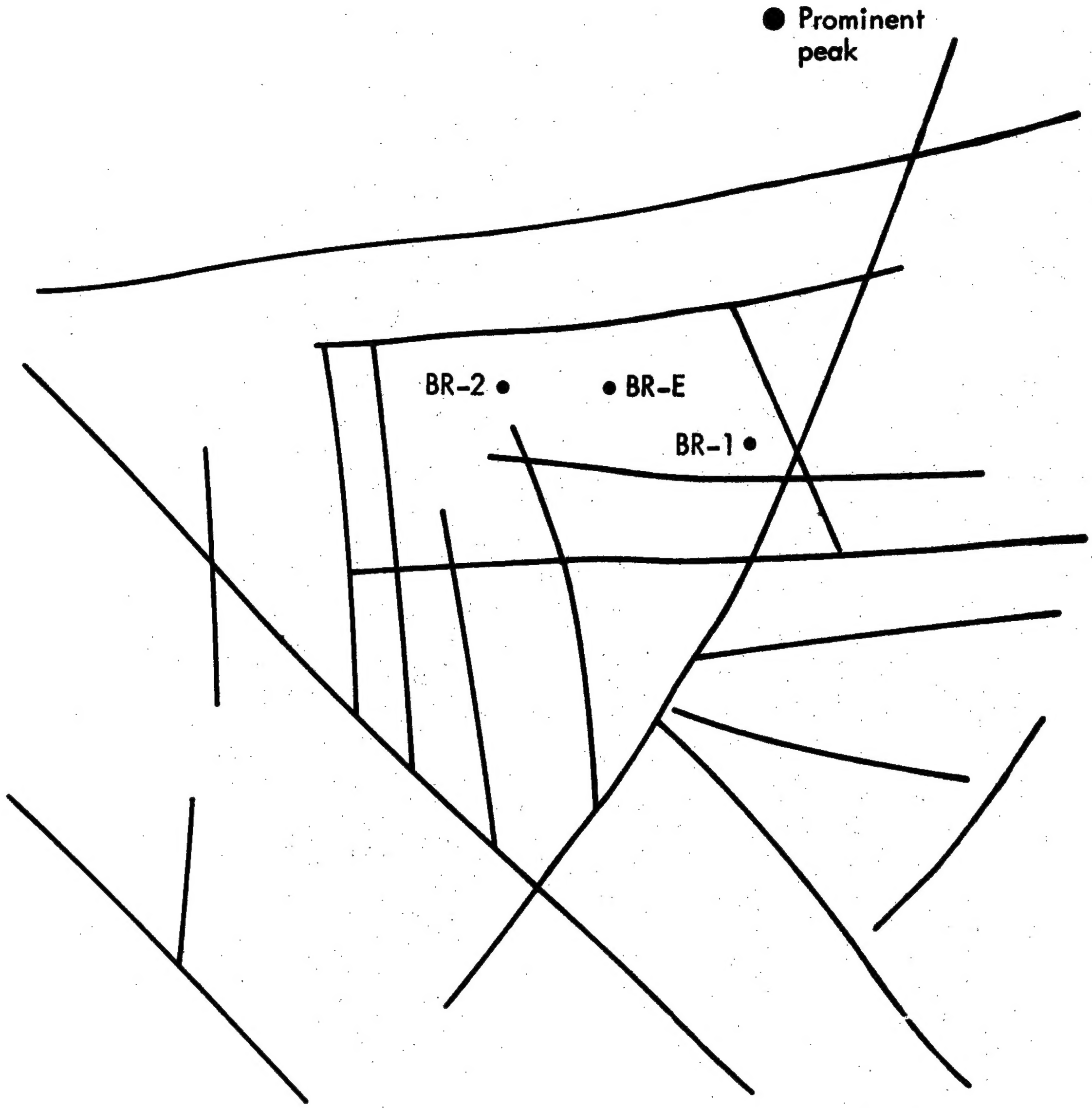


Fig. 3. Tentative Broncho site area, showing the major surface delineaments.

active ranches within 4 miles of the site. However, White River Valley 6 miles to the northeast contains several ranches. The nearest centers of population are Rangely and Meeker, each about 23 miles from the site. Rifle is 38 miles away, Grand Junction 80 miles away.

The geologic fence diagram of Fig. 4 summarizes the stratigraphic features from nearby drill holes.[8,12] Since the geology of the Piceance Creek Basin tends to be uniform over short distances, it is presumed that this projection is reasonably accurate for the tentative site. A continuous



Prominent peak
BR-2
BR-E
BR-1

oil shale section about 1200 ft thick, and averaging over 20 gallons per ton, is expected. The total oil shale interval, with some short barren zones, may be more than 2000 ft thick. The bottom of the richer oil shale is estimated to occur at a depth of between 3000 and 3500 ft in this location.

Although a major aquifer was encountered about 1200 to 1300 ft above the bottom of the oil shale in Core Hole No. 1,[13] the hydrologic conditions are difficult to predict at the recommended site because the hydrology in the basin, unlike the geology, may not be uniform. On the basis of hydrologic tests conducted in Core Hole No. 1, it is expected that at least one aquifer will overlie the proposed shot point. Tests in the lower section of Core Hole No. 1 were inconclusive although they indicate some water. If the base of the upper aquifer is far enough above the shot point, and if the capacity of the lower zone is not too large, the site will be judged to be hydrologically acceptable. If, however, tests in the initial wells at the site indicate sufficient water present to interfere with an in situ retorting experiment, it will be necessary to find a new site or to consider de-watering the lower zone in the area.

It should be emphasized that the area has not yet been formally designated as a site for Project Bronco. Should this site prove unacceptable after exploration by drill holes, an alternate site will have to be found. Two likely looking areas have been identified; both lie between the present suggested site and Yellow Creek. Should the difficulty be hydrological, it may be necessary to search for a site further removed from this area, using the original technical criteria as guidelines.

EXPLOSION EFFECTS

It is proposed to use a nuclear explosive of about 50 kt energy yield. This yield range has been selected because it is large enough so that the cavity created by the explosion will probably collapse, and small enough that only minimal effects are expected from the seismic wave generated by the explosion.

The actual depth of the explosion will be determined after a preshot investigation drilling program at the nominated site. The detonation point will be selected near the base of the oil shale so as to ensure that the collapse chimney will be contained entirely within the oil shale sequence. At this depth the chance of fracture communication between the chimney and overlying aquifers is minimized. While such communication would not contaminate any potable water supply, the inflow of large quantities of water in the chimney would complicate and add to the cost of those phases of the experiment in which recovery of oil is an objective.

For purposes of these calculations it is assumed that the depth of explosion is 3350 ft,estimated from the fence diagram of Fig. 4. The scale depth of burial is 910 ft/kt$^{1/3}$, about twice that of most explosions at the Nevada Test Site. This depth is considered more than adequate to insure containment of the explosion.

According to Higgins and Butkovich,[13] the radius of a cavity created by a contained underground nuclear explosion can be estimated by use of the expression

$$R_c = C \frac{W^{1/3}}{(\rho h)^{\alpha}}$$

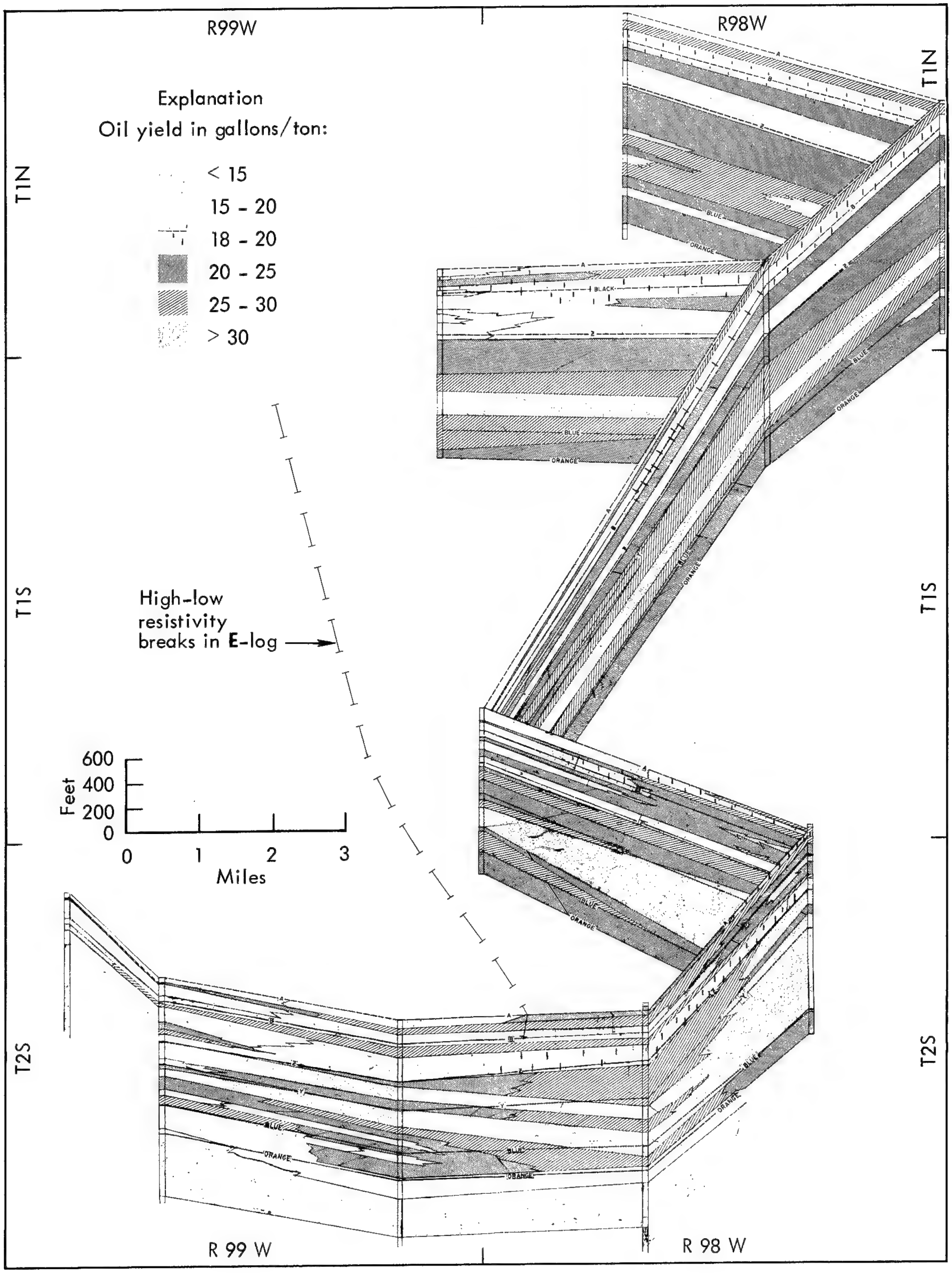
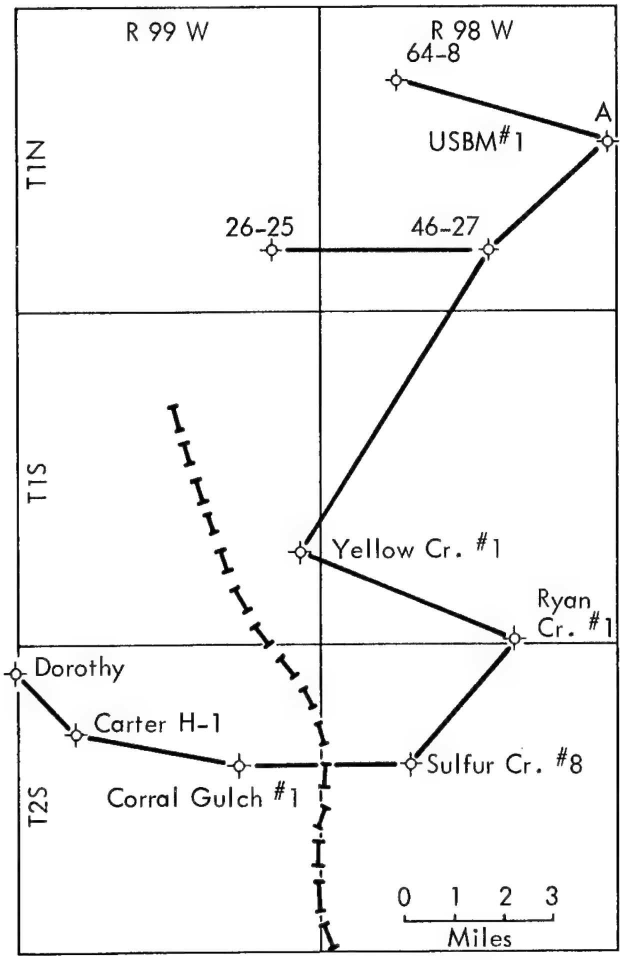
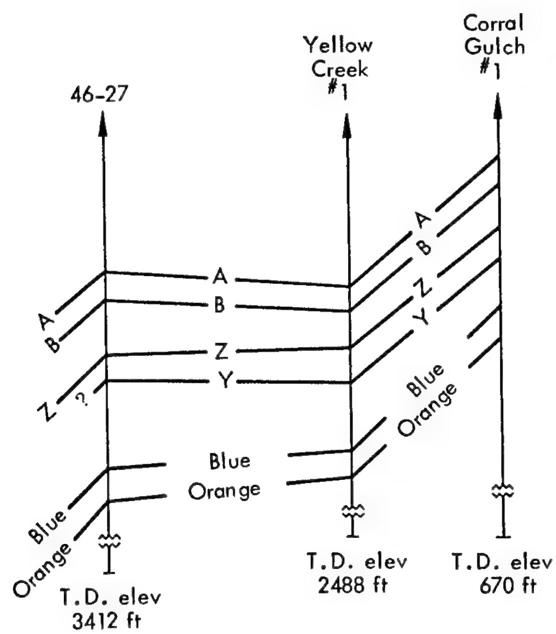


Fig. 4A. Geologic fence diagram showing stratigraphic features.

Drill hole	Elevation (ft)	A marker depth (ft)
64-8	6160	1-20
USBM #1	6003	1070
46-27	6632	1020
26-25	6753	740
Yellow Cr. #1	6604	1120
Ryan Cr. #1	6732	1300
Sulfur Cr. #8	6500	650
Corral Gulch #1	6730	320
Carter H-1	6936	35
Dorothy	7294	0 ?





Source of data other than USBM oil assays:

USBM #1: Depth = 1070-2600 ft, density and acoustic logs (R. D. Carroll, USGS, private communication);
Depth 2600-2950 ft, extrapolated from 46-27 and 64-8.

46-27: E-log and extrapolation from USBM #1, 64-8, and 26-25 drill holes.

64-8: Depth 1020-1950 ft, E-log and extrapolation from USBM #1;
Depth 1950-2805 ft: USBM oil assays.

Fig. 4B. Index map and profile showing elevations of 3 core holes from geologic fence diagram. Figures 4A, B adapted from Ref. 8.

where

R_c = cavity radius (m)

W = explosive yield (kt)

ρ = average specific gravity of overburden

h = depth of burial (m)

α = adiabatic expansion coefficient, a function of water content

C = a constant, a function of rock type.

In Bronco, W will be 50; h will be about 1.02×10^3; and ρ will be about 2.3. To find α, the organic material in the oil shale is assumed to behave like water during cavity expansion. Any error introduced by this assumption should not exceed the error in estimating the value of C. It is also assumed that the oil shale in the immediate vicinity of the shot point has an average grade of 18 gallons per ton.

The hydrocarbon content of this oil shale would be about 10% by weight,[14] and α = 0.298 from Higgins and Butkovich.[13] Of the inorganic matter in oil shale, half is dolomite and half consists of feldspars, quartz, clays, etc. From the table for various rock types, C = 89 for dolomite and 103 for granite, which is rich in the silicates. The value of C for oil shale is therefore assumed to be halfway between these limits, C = 96.

Thus,

$$R_c = 0.96 \times 10^2 \frac{(50)^{1/3}}{(2.35 \times 10^3)^{0.298}}$$

$$R_c = 35.0 \text{ m} = 115 \text{ ft}.$$

The chimney height is assumed to be 4.5 cavity radii or 158 m (520 ft), measured up from the shot point. This is consistent with a bulk porosity of about 25% in the chimney collapse rubble. If these predictions are correct, the chimney will contain about 1.15×10^6 tons of fragmented oil shale. The surrounding fractured region will contain considerably more. The corresponding oil content of the chimney alone, assuming an average of 24 gallons per ton, will be about 660,000 barrels.

Although improbable, it is possible that chimney collapse will not occur. At least one case of a standing cavity and two cases of partial collapse have been documented. In the eventuality of insufficient collapse in Bronco, the experimental plan may be expanded to include one or more attempts to induce further collapse in the oil shale overlying the cavity.

Data on which to base predictions of the extent of fractures around an underground nuclear chimney are sparse. Under some conditions, however, enhanced fracture permeability to a distance of two to four cavity radii laterally beyond the edge of the nuclear chimney has been observed.[15] In at least one case, postshot drilling has indicated the existence of explosion-produced fractures as much as 6 cavity radii above the detonation point.[16] It is not yet clear which of several postulated mechanisms is responsible for the observed fracturing, and mathematical models which predict fracturing have not yet been confirmed.

On the basis of previous experience it is estimated that the Bronco detonation will fracture as much as 460 ft laterally beyond the chimney edge and to as far as 700 ft above the shot point.

DESCRIPTION OF THE BRONCO EXPERIMENT

The Bronco Experiment is organized into four phases:

Phase I Site Confirmation
Phase II Construction, Detonation, and Evaluation
Phase III Chimney Treatment
Phase IV Fracture-Zone Treatment

Breaks between phases occur at times in the project corresponding to major decision points for participants. A description of each phase follows.

PHASE I: SITE CONFIRMATION

The main purposes of Phase I are to evaluate the geologic and hydrologic conditions and to establish that the site is satisfactory from technical and safety viewpoints. Three wells, BR-1, BR-1W and BR-2, will be drilled to determine the oil shale thickness, grade and uniformity; the overburden thickness; the occurrence and orientation of fractures; presence of other minerals; and the existence and transmissibility of water zones. The locations of these wells in the tentative site area are shown in Fig. 5, which also gives a cross-sectional view in elevation of the wells. The technical specifications are summarized in Table I.

The decision by both government and industry participants regarding the technical acceptability of the site will be made after the data from BR-1, BR-2, and BR-1W are analyzed.

Well BR-1 — This will be drilled approximately 400 ft from the proposed emplacement hole location. The well will be mist-drilled and cored from the Mahogany Marker (estimated ~1480 ft) to the hole bottom at 3900 ft. Minimum core diameter will be 3-7/8 in. with maximum recovery attempted. Past experience indicates that special care will be required to recover core through the upper naturally fractured shale interval to about 2150 ft, the estimated top of the competent shale zone. Drill stem tests will be taken of water entry zones encountered while drilling. Fluid levels, bottom hole pressure build-ups and selected interval spinner tests of water zones will be taken. Fluid injection tests to determine fracture conductivity may be required. During periods when the hole is left standing, the shale member below the water zones should be packed off or otherwise protected to prevent recharge of possible lower permeable zones. The well will be cemented back to casing shoe after completion of the hydrologic flow-transmissibility tests between BR-1 and BR-2. A complete suite of logs will be taken.

Well BR-2 — The primary purpose of Well BR-2 will be to conduct hydrologic transmissibility tests to BR-1 and possibly to BR-3, which is to be drilled as an instrument hole in Phase II-A. A second purpose is to confirm the geology at the site determined in BR-1. BR-2 is to be drilled 300 ft from the emplacement location at a point opposite to BR-1 and to a total depth of approximately 3500 ft. Final determination of depth will be on

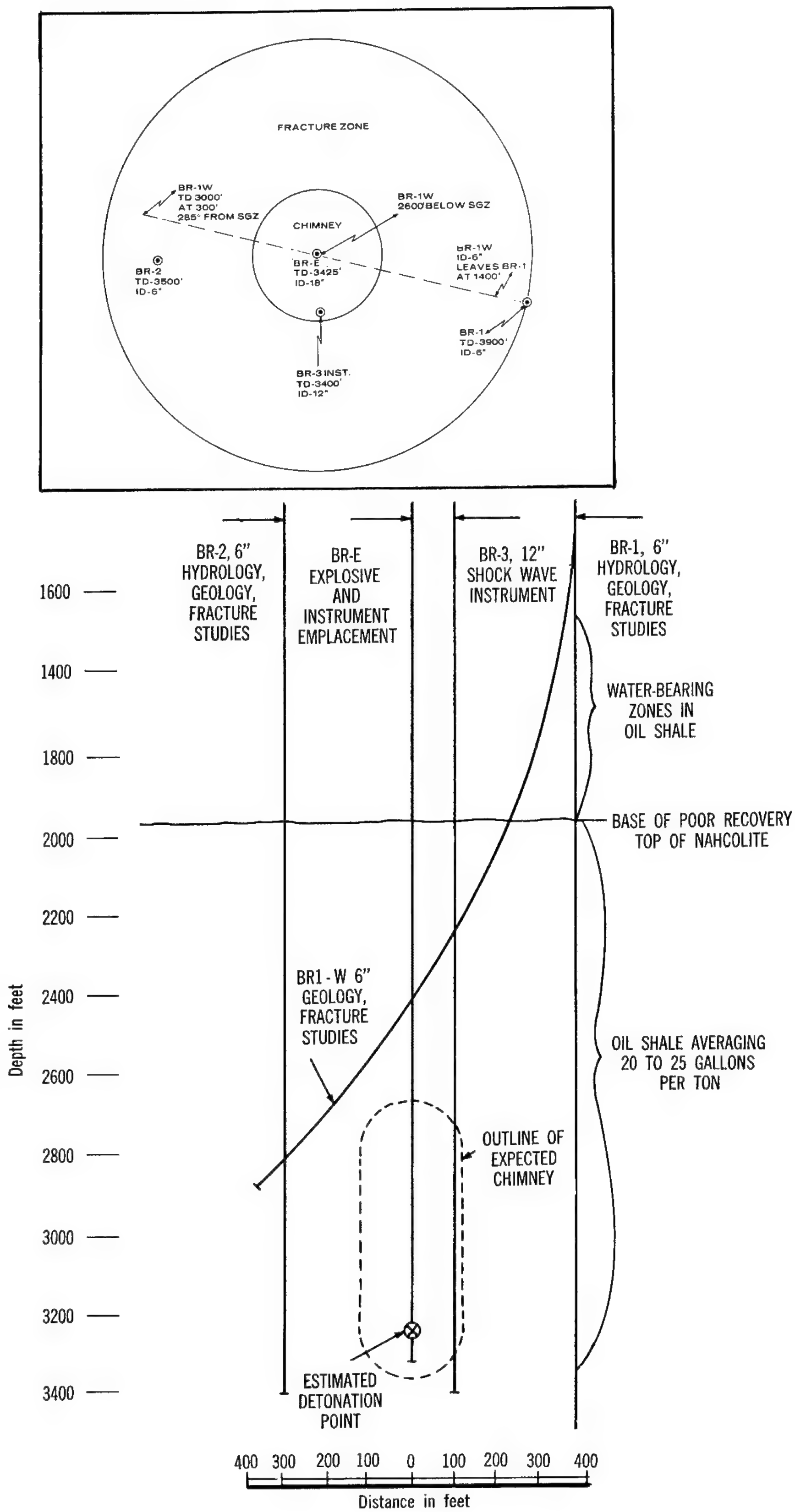


Fig. 5. Phase I and Phase IIA (Preshot) wells.

Table I. Well specification for Phase I site confirmation.

	BR-1	BR-1W	BR-2
Purpose	Geologic Hydrologic	Geologic Vertical fractures	Geologic Hydrologic
Distance from GZ	400 ft	Deviated toward and beyond emplacement from BR-1	300 ft
Total depth	3900 ft	3000 ft	3500 ft
Minimum ID	6 in.	6 in.	6 in.
Drilling fluid	Mist below casing shoe (CS)	No requirements	Mist below CS
Casing and depth	7-5/8 in. at 1400 ft	Re-entry of BR-1	7-5/8 in. at 1400 ft
Cementing	Material balance to surface		Material balance to surface
Core interval (3-7/8 in.)	1450 to 3600 ft	300 ft total	2100 to 300 ft 2700 to 3500 ft
Logging	IES* γ - N** Sonic Density Caliper Direction survey Photography	IES γ - N Sonic Density Caliper Direction survey Photography	IES γ - N Sonic Density Caliper Direction survey Photography
Hydrologic tests	Swab during drilling Packer-flow Spinner-packer Flow tests to BR-2	Injection Packer-flow Spinner-flow	Pressure monitoring with BR-1 and BR-3
Completion	Plugged to 1400 ft after tests. Stemmed to surface for later re-entry in BR-1R	Plugged to 1400 ft with cement	Instrument grouted to surface before detonation
Instruments			2 clipers (2 cables)

*Induction-electric survey.

**Gamma-neutron.

the basis of logs and core from BR-1. The hole should be cased to approximately 1400 ft. Flow or pump tests between Well BR-2 and holes BR-1 or BR-3 should help to distinguish the block-joint orientation in the upper water filled zone above the competent shale zone. A 3-7/8 in. core will be taken from about 2100 to

2300 ft to confirm the interface between the upper fractured interval and the lower competent oil shale, expected at about 2150 ft. Core will also be taken opposite the anticipated chimney zone from 2700 ft to 3500 ft. Short sections of core may also be taken opposite other interesting intervals found in the BR-1 well. Complete logs will be taken in the hole.

In order to help define the fracture mechanism during the nuclear detonation, Phase II-B, a fracture cliper* gauge will be run and grouted over the entire open hole interval. In order to monitor hydraulic pressure in the major water-bearing section during and after detonation, one or more remote-reading pressure gauges may be cemented in BR-2.

Well BR-1W — The purpose of Well BR-1W is to investigate the occurrence of vertical fractures or faults above the anticipated nuclear chimney. Such fractures, extending deeply into the competent shale zone from the upper aquifer system, might present hydrologic problems of postshot communication to the chimney or safety problems related to the explosion. After the hydrologic tests between BR-1 and BR-2, Well BR-1 will be plugged back to 1400 ft and a whipstock BR-1W will be started in the direction of the emplacement location. The BR-1W hole should pass over the detonation point at a depth of about 2600 ft and will extend about 300 ft beyond the proposed emplacement location to an approximate depth of 3000 ft.

Approximately 300 ft of 3-7/8 in. core will be taken. A full suite of logs will be obtained over the interval 2000 ft to total depth. Should it appear that BR-1W has intercepted a major vertical fracture or a permeable network, tests will be made. These tests may include either injection of air or production of fluid so that the extent and capacity of the fracture interval can be estimated. The hole will be completely filled with cement shortly after testing because BR-1W is expected to pass near the fractured interval created by the explosion.

Core Analysis — Fischer assay at approximately 1-ft intervals as indicated by lithologic examination of the core will be taken to determine the oil content. The core will also be examined for nahcolite, dawsonite and halite.

Geophysical Logs — These will at least include IES (induction-electric survey), γ-N (gamma-neutron), sonic, density and caliper logs. Directional surveys of all wells will be required. Microseismogram or other acoustic amplitude logs will be taken for fracture and formation interpretation.

Hydrologic Tests — The hydrologic testing will consist of swab tests with fluid level and pressure buildup measurements during drilling. After drilling, pump tests for extended periods will be made to determine the transmissibility and capacity of the zones. Packed zone spinner surveys, pressure drawdowns, and buildup analyses of flow capacity will be included as needed. Constant rate pumping from one well while monitoring with downhole instrumentation will be done for between-well tests.

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*A cliper is a down-hole coaxial cable providing an open circuit when fractured. The time record of the electrical length of severed cable defines the depth of occurrence of horizontal fractures. It may be used to monitor chimney collapses.

Fracture Studies — These will be conducted in preshot and postshot holes and may involve the use of borehole photography, spinner-monitored air or gas injection and impression packers.

PHASE II: CONSTRUCTION, DETONATION, AND EVALUATION

Once the tentative Bronco site has been shown to satisfy the geologic, hydrologic, and safety criteria, the major construction for the nuclear experiment will begin. Plans for Phase II call for:

1. Drilling an instrument hole (BR-3) and an emplacement hole (BR-E).
2. Installing instrumentation required for scientific measurements and safety documentation.
3. Emplacing and detonating the nuclear explosive.
4. Re-entering the explosion environment, evaluating any hazardous conditions, and establishing appropriate safety procedures for the remainder of the experiment.
5. Investigating the nuclear chimney and fractured zones in preparation for subsequent in situ treatment. Measurements will be made of the chimney dimensions; rubble size distribution and void volume; radioactivity levels, species, and mode of occurrence; temperature and pressure levels; and fracture extent, fracture density, and fracture permeability.

Data from Phase II will allow a more definitive design for the treatment phases of the experiment. Specific well locations in the postshot program may be changed as a result of data obtained on preceding wells.

Phase II is further divided into three subphases:

Subphase II-A: Preshot construction
Subphase II-B: Detonation
Subphase II-C: Evaluation

Subphase II-A: Preshot Construction

In addition to normal site construction of roads, trailer pads, etc., two wells, BR-3 and BR-E, are required. The locations of the wells are shown in Fig. 5. Specifications for the wells are given in Table II.

Well BR-3 — This well will be drilled 100 ft from the emplacement location. Although its primary purpose is that of an instrument hole for monitoring and recording explosion-associated phenomena, it will afford an additional opportunity for coring or testing of the formations if deemed advisable after examination of Phase I data. BR-3 will be a 12-in. minimum ID well with 13-3/8 in. casing through the upper water zones to approximately 2300 ft, and to a total depth of about 3400 ft. Oil shale intervals previously missed, or intervals of interest as determined from wells BR-1 and BR-2, will be cored. Wet hole logs will be taken over the entire well. Hydrologic tests in BR-3 with pressure monitoring in Well BR-2 may be desirable while drilling, although extensive testing is not planned.

Well BR-E — This emplacement well will be drilled to a total depth of 3425 ft and sized to take an explosive at least 18 in. in diameter. The well is to be cased below the surface waters but no specific deeper casing requirements are necessary,

Table II. Well specifications for Phases II-A and II-B.

	BR-3	BR-E	B-4	BR-5
Purpose	Instrument	Emplacement	Chimney re-entry injection	Radiation samples and production
Distance from GZ	100 ft	0	25 ft	160 ft
Total depth	3400 ft	3425 ft	To chimney top ~2800 ft	3400 ft Whipstock from 3200 to 3500 ft
Minimum ID	12 in.	>18 in.	9-5/8 in. below CS	6 in.
Drilling fluid	mud	mud	Mud to CS Gas below CS	Mud to CS Gas below CS
Casing size and depth	13-3/8 in. to 2300 ft	24-in. conductor to 400 ft	13-3/8 in. to 2300 ft	7-5/8 in. to 2300 ft
Cementing	Material balance to surface		To surface	To surface
Cores (3-7/8 in.)	Approx. 200 ft	None	2300 ft to chimney	2300 ft to TD whipstock
Logging	IES γ-n Sonic Direction survey Caliper	IES γ-n Sonic Direction survey Density Caliper	γ-n Temperature Radiation Direction survey Caliper	γ-n Temperature Radiation Direction survey Caliper
Testing	Swabbing while monitoring BR-2	To pass a mandrel	Gas samples Photograph Pressure up	Gas samples Photograph Flow from chimney
Completion	Instrument loaded—grouted to surface	Load explosive and stem to surface	Recompleted injection well for Phase III	Recompleted for post-treatment coring in Phase III and as production well in Phase IV
Instrumentation	2 peak pressure 3 3-component stress gauges 6 time-of-arrival switches (12 cables)	2 peak pressure 3 cliper 2 slifer (9 cables)		

since the well will be appropriately stemmed and will not be re-entered after the shot. The nuclear explosive will be emplaced in mud and the hole will be stemmed to the surface. Logs will be taken in the well for correlation purposes. The specific shot depth will be determined from the logs and the correlative data from BR-1 and BR-2.

General Construction – All-weather access roads, the trailer pads, and the control-point (CP) and recording trailer park (RTP) will be constructed during Phase II-A for primary occupancy during Phase II-B. The surface topography of the entire area is such that many potential sites are available for CP and RTP with a minimum of clearing and leveling required.

Communication facilities will be constructed from existing telephone service to the CP and ground zero (GZ) locations. Cableways for shot-associated instrumentation and firing will be graded from the BR-E, BR-3 and BR-2 wells to the CP and RTP area.

A building near GZ is required for final assembly of the explosive and checkout. Fencing and guard houses are needed at GZ and the CP.

Subphase II-B: Detonation

The Atomic Energy Commission will be responsible for the safety program associated with the nuclear explosion. Weather studies, radioactivity monitoring, and seismic measurements will be essential elements of the safety program. Specifications for wells to be drilled in this subphase are given in Table II. The well locations are shown in Fig. 6.

Dynamic motion sensors will be loaded into holes BR-3 and BR-2 and cemented to surface. Hole BR-3 will be fitted with a string of peak pressure gauges, stress history transducers and velocity slifers* to give data on the variation of shock wave characteristics with distance and time. The emplacement hole, BR-E, will also contain similar gauges in addition to cavity collapse detection instruments. Fracture cliper instrumentation will be cemented in BR-2.

The explosive will be transported to the site and emplaced in BR-E with its associated instrumentation. The well will be stemmed, i.e., backfilled, for full containment in a manner based on previous experience. The cementing in the preshot holes will be conducted with strict material balance control, including caliper surveys, to insure that no channels exist for the escape of radioactivity during the explosion and also to insure a low probability of communication between overlying water zones and the nuclear chimney.

Weather will be monitored for the event even though the possibility of any release of effluent material above the ground surface is extremely remote. If conditions are unfavorable the explosion will be postponed.

Ground surface motion will be measured at several locations within a few miles of surface zero. Seismic motion will be measured at selected ranches and nearby population centers.

*A slifer is a coaxial cable arranged more or less radial to the detonation point. The advancing shock wave generated by the explosion crushes the cable. Electronic instrumentation continuously measures its electrical length, i.e., the length of unshorted cable. Analysis of the data gives shock front position as a function of time.

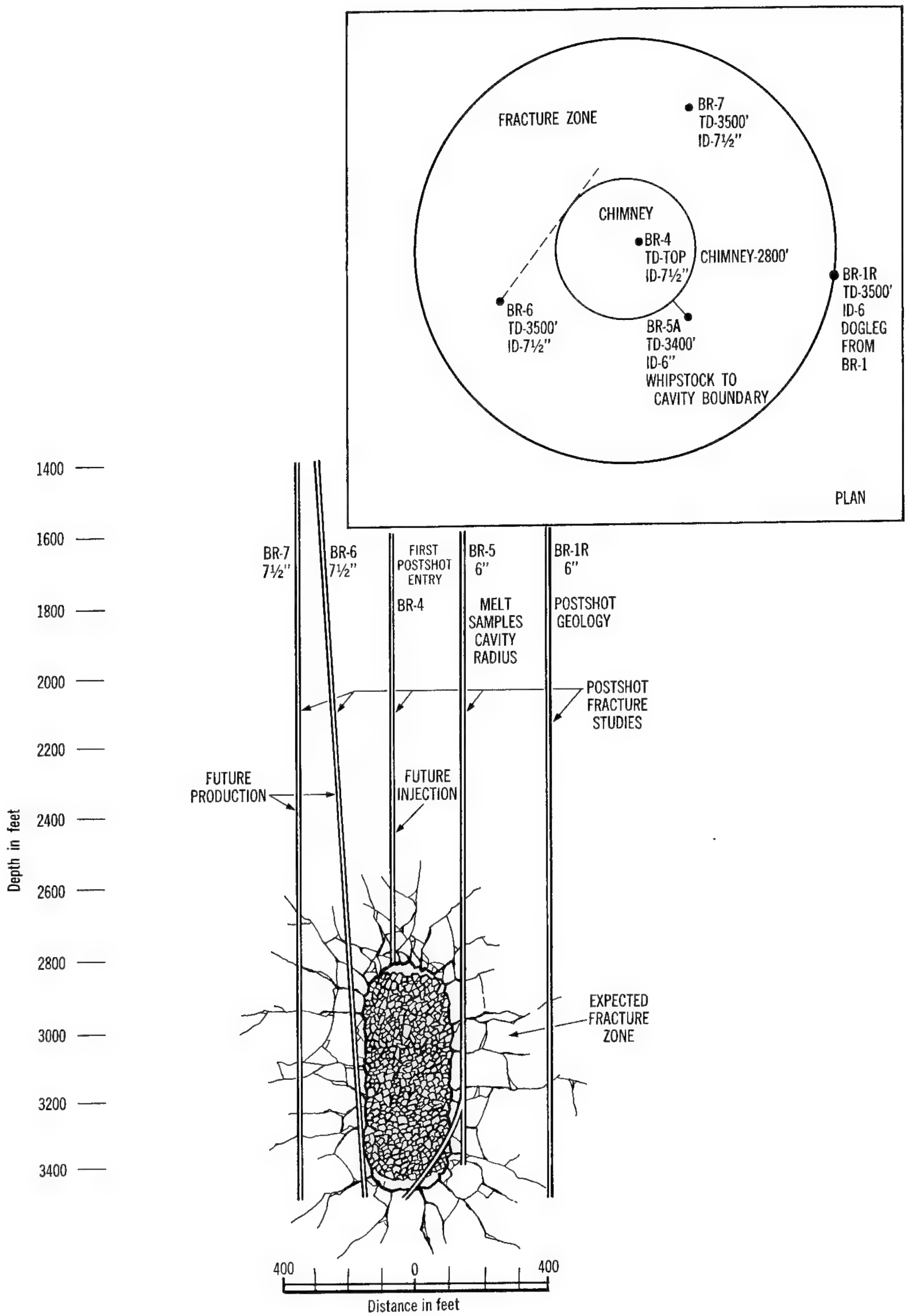


Fig. 6. Phase IIB and Phase IIC wells.

Well No. BR-4 — This will be the first re-entry well into the top of the chimney; drilling will start as soon as possible after the shot. The well will be located 25 ft from the emplacement location BR-E. It will also be used later as an injection well in Phase III. Therefore the drilling program will be: cement 18-in. conductor pipe to surface through surface waters; drill with mud through the upper, naturally fractured water bearing zones and into the top of the competent shale zone at about 2200 ft; cement 13-3/8 in. casing into the competent shale zone to about 2300 ft; change over to gas or mist drilling below 2300 ft, taking 3-7/8 in. core from the casing shoe to the top of the chimney. Care will be taken to insure maximum core recovery.

Pressure, temperature, and radioactivity measurements will be made during drilling. Logs and temperature surveys together with downhole photography will help determine the height of the explosion-created fractured interval above the chimney. The hole will be used for taking early samples of the chimney gas for chemical and radioactivity analyses. Photographic studies of the top of the chimney rubble will help define rubble size distribution. Chimney volume and wall rock average permeability will be measured by gas injection and pressure fall off techniques.

Well No. BR-5 — This well will be drilled parallel to the chimney wall about 160 ft from the emplacement location. The exact distance will depend upon the approximate radius of the chimney as determined by the pressure experiments in BR-4. The well will be cased with 9-5/8 in. casing into the competent shale member below the water and inert gas cored from that depth to a total depth of 3400 ft. During drilling, gas samples will be taken every 100 ft opposite the chimney interval. The samples will provide radioactivity values at various levels in the chimney in communication through fractures to the well bore. Complete dry hole logs will be taken. Downhole impression blocks, packer spinner runs, photography or television may be used to assist in determination of fractured intervals. A drillable plug will be inserted at approximately 3200 ft and a whipstock will be made to intersect the chimney wall at the approximate detonation level. This whipstock will be used to define the chimney boundary and also will be continued through the bottom of the chimney to obtain melt samples for explosive performance studies.

Radioactivity — The gas, fluid, and core specimens taken in Phase II-B will be used in the radioactivity study. In addition, it may be desirable to flush the chimney by injecting inert gas into BR-4 and flaring (if safe) the return gas from BR-5. If levels of radioactivity are too high, the flaring experiment may be postponed until Phase III.

Radiation measurements will be made during postshot drilling to assess the nuclear chimney environment and to assist in planning subsequent safety programs. During Phase II-B the site will be strictly monitored for radioactivity levels. Blowout preventers will be used and positive control of drill cuttings and return gas will be maintained. Radioactive cuttings will be recovered for analysis and disposal; return gas may be highly diluted and stack flared. A high pressure gas recirculation system will be employed. Oxygen will not be admitted to the system or the chimney.

A delay to allow for radioactive decay may be indicated. The remaining postshot environment investigation wells in Phase II-C will not be drilled until the radiation problem has been assessed from BR-4 and BR-5.

Precautions with BR-4 and BR-5 — Care will be taken with both wells to insure that the upper water zones are cased off so as to prevent communication with and subsequent flooding of the chimney. The chimney and fractured zone should be kept dry if possible to prevent subsequent problems in Phases III and IV. Testing of the hydrology in the upper interval will not be necessary, although pressure levels in the zone should be measured while drilling to determine whether there is apparent communication with the chimney.

Subphase II-C: Evaluation

The intent of this postshot program is to perform a thorough evaluation of the nuclear chimney-fractured area complex to determine whether an in situ treatment can be carried out.

Three holes, BR-1R, BR-6 and BR-7, will be drilled to establish the nature and extent of fracturing surrounding the chimney. In addition to being used in investigating the fracture system, they will later become a part of the oil recovery phases. Specifications for the wells are given in Table III. The relative locations of the wells are shown in Fig. 6.

Table III. Well specifications for Phase II-C.

	BR-1R	BR-6	BR-7
Purpose	Core-fracture	Fracture, production	Fracture, production
Distance from GZ	400 ft	250 ft	300 ft
Total depth	3500 ft	3500 ft	3500 ft
Minimum ID	6 in.	7-7/8 in.	7-7/8 in.
Drilling fluid	Gas	Gas	Gas
Casing size and depth	Existing BR-1	13-3/8 in. to 2300 ft	13-3/8 in. to 2300 ft
Cementing	—	To surface	To surface
Cores (3-7/8 in. diam.)	2300 to 3500 ft	CS to 3500 ft	CS to 3500 ft
Logging	γ-n Density Temperature Deviation survey	γ-n Density Temperature Deviation survey	γ-n Density Temperature Deviation survey
Testing	Injection spinner Pressure monitoring	Impression block Injection spinner Photography	Impression block Injection spinner Photography
Completion	Open-hole packer and tubing below water	Recompleted in Phase III for production	Recompleted in Phase III for production

Well BR-1R — This well will be a re-entry of BR-1 with deviation at about 1400 ft. A 3-7/8 in. core will be taken to a total depth of 3500 ft. Complete geophysical logs will be taken. The object is to compare BR-1R information with the preshot cores and logs taken at the same location in BR-1.

Well BR-6 — This will be a new well located 250 ft from the emplacement hole. Although its primary purpose is fracture investigation outside the chimney, it will be cased with 13-3/8 in. casing into the competent shale zone below the natural water system in such a way that it can be enlarged during the Phase III chimney treatment for use as a production well. It is to be drilled with inert gas, cored below the casing to 3500 ft and slanted to graze the cavity radius near the base of the chimney on the northwest side. Complete logs will be taken and down-hole tests will be made in the well to study fractures. These tests may include injection spinner runs with packers, photography, and impression packers.

Well BR-7 — This will be a straight well located 300 ft from the emplacement location opposite BR-6. Like BR-6, it will be cased into the competent shale zone with 13-3/8 in. casing for future use in Phase III as a production well. Core and logs will be taken and tests will be made in the straight hole for fracture location, fracture density and permeability determinations. On completion of these tests the straight hole will be plugged back so that a larger slant hole can be drilled into the base of the chimney and completed as a production well in Phase III.

Fracture studies in all postshot holes will include examination of the core and geophysical logs, downhole photography, the impression packer where indicated, and gas injection with packer-spinner gauge. Directional surveys will be taken in all wells to determine the geometry of the induced fracture system. Postshot cores will be examined for fractures bearing radioactive material. Analysis of such fractures may help to reveal at what time they developed during cavity and chimney formation. This information will help to indicate whether the fractures were caused by the outgoing shock wave, by the collapse which formed the chimney, or by subsequent relaxation and stress adjustment in the medium. When the mechanisms are more clearly understood, better fracture prediction will be possible.

PHASE III. CHIMNEY TREATMENT

Phase III consists of a full-scale experimental treatment of the oil-shale rubble in the chimney. Its purpose is to assess the technical and economic feasibility of the method or methods chosen, by measurement of process parameters and by examination of the products. The following key questions will be asked in this phase: What proportion of the potential shale oil can be recovered? Is there radioactivity in the product oil? If so, what is its distribution? What are the effects of important control variables such as air recycle gas ratio upon measured results such as temperature distribution and gas composition?

The preliminary Phase III design is based on retorting with the heat generated by combustion of the carbonaceous residue in retorted oil shale.

This design will probably be modified prior to the execution of Phase III as more technical information becomes available from BuMines retorting experiments, from theoretical studies of the retorting process, and from prior Bronco investigations. Furthermore, industrial research on other retorting methods, including the use of preheated inert or reactive gas (without in situ combustion) may suggest the testing of one of these techniques in Bronco. In this present definition of the experiment it is assumed that:

1. The chimney dimensions are 115 ft radius and 520 ft height.
2. The grade distribution of oil shale in the chimney is the same as that in Core Hole No. 1.[13]
3. No pressure problems are present other than those associated with fluid flow. The chimney exists as a closed retort and there is no uncontrollable inflow of water.
4. The technique of in situ combustion of residual coke in spent shale is used following an initial period in which hot natural or combustion gases are injected to preheat the top of the bed. After this preheating, air will be injected with or without natural gas to attempt uniform ignition over the bed. The design includes the option of recirculating a fraction of the off-gas.
5. The experimental data on retorting front advance rates and air volume requirements, accumulated by the Bureau of Mines at Laramie in retorting unsorted mine run shale up to 20 in. in two dimensions, are applicable in scaling to the nuclear chimney. This scale up factor is approximately 10^5 on a total volume basis.

The foregoing assumptions imply that the chimney will contain about 1.15×10^6 tons of oil shale. However, some oil shale in the chimney wall will be retorted as well. Thus for the purpose of making retorting calculations, it is assumed that the retorting will affect 1.3×10^6 tons of oil shale at an average grade of 24 gallons per ton containing about 3.1×10^7 gallons of shale oil of which 80% may be recoverable. This is equivalent to a recovery of 2.5×10^7 gallons or 5.9×10^5 barrels of shale oil.

Analysis of data from the BuMines 10-ton retort suggests that an average downward advance of the retorting front in the nuclear chimney could be as low as 1.5 ft per day. At this rate, 360 days would be needed to treat the 520-ft Bronco chimney. Extrapolation of data from the retort indicates that an air injection rate of approximately 11,000 scf/ton would be required to treat oil shale. With the use of recycle gas, the total flow requirement would be about 18,000 scf per ton.

The Bronco chimney is expected to be thermodynamically more efficient than the Laramie retort. The latter leaves about 1/3 of the heat generated by combustion in the 1000°F spent shale at the conclusion of retorting. The corresponding spent shale temperature in Bronco is expected to be closer to 400°F, since the input gas temperature from the compressor is estimated to be about 310°F. The requirement for heat — and thus for air — in Bronco would be reduced. For design purposes, an air requirement of 8250 scf/ton and an air-plus-recycle-gas requirement of 13,500 scf/ton is assumed. A total of

1.75×10^{10} scf of air and gas will be needed. The average daily rate will be 4.9×10^7 scf for 360 days.

If all the oil is produced as a liquid, and if 80% recovery is assumed, the average daily pumping rate will be about 1650 barrels/day.

To provide for the necessary gas flow at a pressure drop of a few atmospheres requires three injection wells and three production wells, each with a minimum ID of 12 inches. The locations of these wells are shown in Fig. 7 and the specifications are shown in Table IV. The wells will be furnished as follows:

1. The open hole section of hole BR-4 will be enlarged to a minimum ID of 12 in. to the top of the chimney for use as a gas injection well.

2. New holes, BR-8A and BR-8B, will be located about 75 ft from GZ and spaced equally about GZ from BR-4. These holes will be additional injection wells and will be drilled with mud to about 2300 ft, with 13-3/8 in. casing set into the competent shale. The wells will be gas drilled further to the top of the chimney at about 2800 ft, with a minimum ID of 12 inches.

3. At the Nevada Test Site, drilling into loose, unsorted, widely varying size blocks contained in chimney rubble zones has been difficult and oftentimes costly, but an attempt will be made to place 3-1/2 in. OD drill strings in the rubble to the bottom of the chimney in the injection wells BR-4, BR-8A, and BR-8B. The purpose of these strings would be to provide channels to periodically monitor process variables in the retort bed.

4. Hole BR-6 will be enlarged to a minimum ID of 12 in. and extended into the bottom of the chimney.

5. A new hole, BR-9, will be located about 250 ft from GZ and will be slanted to the bottom of the chimney. It will be completed to 2300 ft with 13-3/8 in. casing cemented to the surface. Below 2300 ft it will be drilled with a minimum ID of 12 inches.

6. Hole BR-7, having been plugged back to the casing shoe, will provide access for a whipstock hole, BR-7P, with a minimum ID of 12 in. slanted to enter the bottom of the chimney.

7. Each of the holes, BR-6, BR-7P and BR-9, will be a production well. A string of 3-1/2 in. OD tubing and a down-hole pump will be inserted in each for use in recovery of liquid shale oil and water. Retort gases will be produced through the annuli of these wells. In the event that additional production capacity is required, Well BR-5 can be similarly equipped in Phase III.

8. The outputs of BR-6, BR-7P and BR-9 will be monitored with automatic equipment for radioactivity and chemical composition. Sufficient equipment will be provided so that the effluent of the three production wells can be processed collectively on line to separate the oil, water and gas phases. Provision will be made for bleeding a fraction of the off-gas to the intake of the compressor system for recycle.

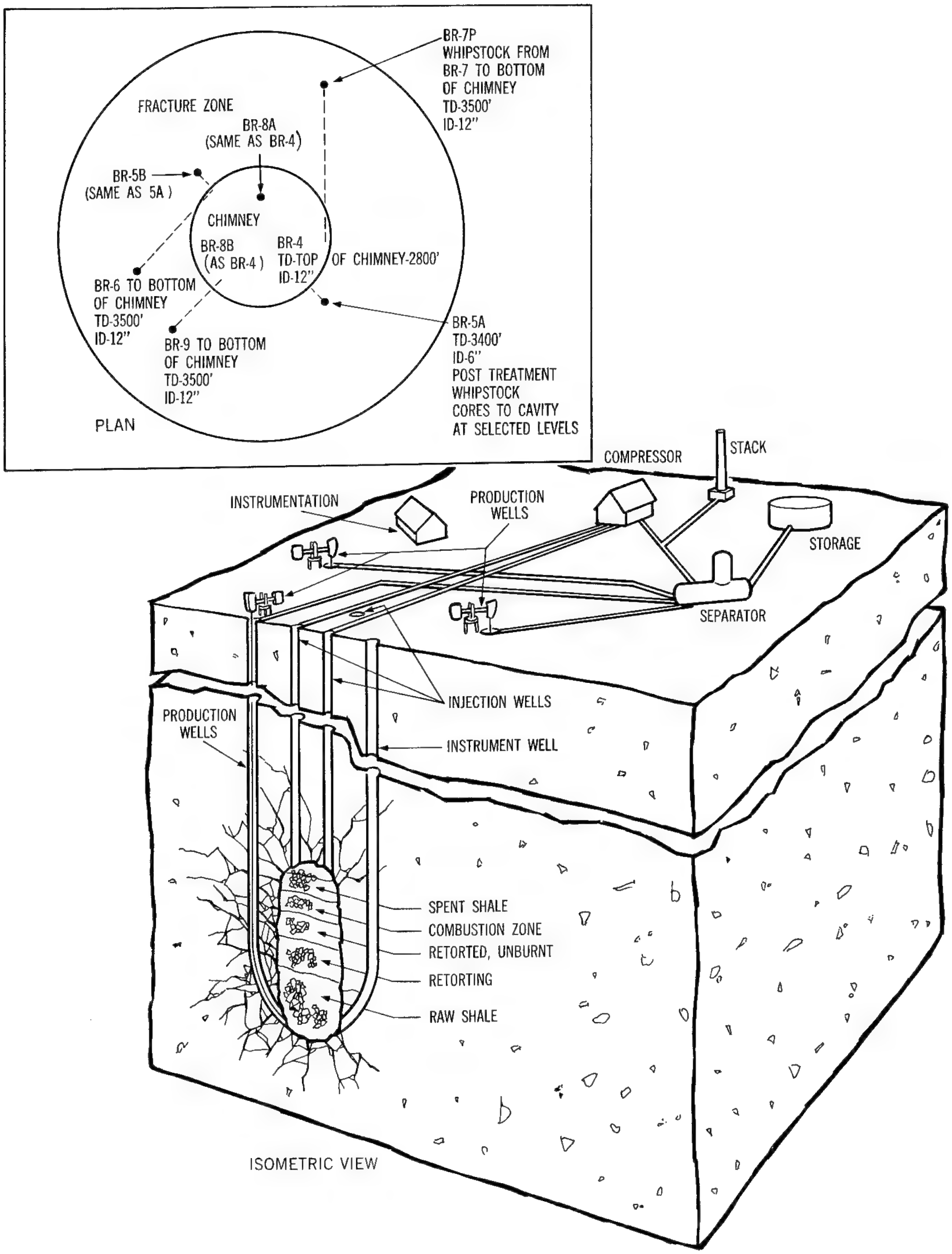


Fig. 7. Phase III wells.

Table IV. Well specifications for Phase III.

	BR-4	BR-5A BR-5B	BR-6
Purpose	Injection and temperature survey	Post-treatment survey near chimney	Production
Distance from GZ	25 ft	~160 ft	250 ft
Total depth	2800 ft	Various	3500 ft
Minimum ID	12 in.	6 in.	12 in.
Drilling fluid	Gas	Mud to CS, gas below CS	Gas
Casing size and depth	Existing	Existing BR-5 for BR-5A-7-5/8 in. to 2300 ft for BR-5B	Existing
Tubing or drill pipe	3-in. pipe to 3500 ft	—	3-in. tubing to 3500 ft
Cement	To surface	To surface	To surface
Core (3-7/8 in. diam.)	None	Whipstock into chimney at selected levels	None
Logging	None	Direction survey Radioactivity survey	Direction survey
Hydrologic tests	None	None	None
Completion	Injection plus drill pipe for surveys	BR-5A recompleted as production well in Phase IV	Production with tubing and liquid pump

	BR-7P	BR-8A BR-8B	BR-9
Purpose	Production	Injection and temperature survey	Production
Distance from GZ	300 ft	75 ft	250 ft
Total depth	3500 ft	2800 ft	3500 ft
Minimum ID	12 in.	12 in.	12 in.
Drilling fluid	Gas	Gas	Gas
Casing size and depth	Existing	13-3/8 in. to 2300 ft	13-3/8 in. to 2300 ft
Tubing or drill pipe	3-in. tubing to 3500 ft	3-1/2 in. pipe to 3500 ft	3-in. tubing to 3500 ft
Cement	To surface	To surface	To surface
Core (3-7/8-in. diam.)	None	None	None
Logging	γ-n Caliper Direction survey Temperature	γ-n Caliper Direction survey Temperature	γ-n Caliper Direction survey Temperature
Hydrologic tests	None	None	None
Completion	Production with tubing and liquid pump	Injection plus drill pipe for surveys	Production with tubing and liquid pump

9. A compressor system will be installed to force gases under pressure into the chimney. It is assumed that the permeability of the chimney itself will be sufficiently great that the pressure drop due to gas flow is injection wells will be about 15 psi and through the production wells about 31 psi. Allowing 6 psi for pressure drop across the chimney and in flaring and at an ambient pressure of 12 psia for the 6400 foot elevation, the input pressure to the injection wells must be about 63 psia. Operating at a pressure in this range at high flow rates, the use of centrifugal compressors is indicated. The power requirement to maintain the expected flow at the pressure ratio required is calculated to be about 6000 brake horsepower. This value is based on use of two multistage compressors in tandem, each at a pressure ratio of 2.345, with intercooling to a temperature of 100°F between compressors. The gas temperature at the injection wells then becomes about 310°F.

10. Aboveground storage will be required for product oil and water. It is proposed to provide on-site tank storage, in increments of 10,000 barrels, for up to 50,000 barrels for storage of contaminated oil. This volume corresponds to the maximum amount of oil which could result from the heat of the explosion.[7] The Bronco experiment is required to determine the amount, degree and mechanism of oil contamination. Consideration will be given to using this oil as fuel to small compared with the pressure drop in the injection and production wells. At the postulated injection flow rate, shared equally by the triple system of wells, it is calculated that the pressure drop through supply part of the heat required during Phase IV. If this is undesirable, the oil could be returned to the chimney at the conclusion of the experiment. In addition, temporary storage capacity of not more than 20,000 barrels should be provided for disposable oil. Furthermore, temporary storage aboveground of about 1000 barrels, should be provided for the saline water effluent of the separation stage. Consideration will be given to reinjection of this water into a saline-water-bearing formation continuously during the experiment. For this purpose, hole BR-1R could be used by insertion of a packer at a suitable depth and the casing perforated over a sufficient interval to handle the volume required.

11. At the conclusion of the chimney treatment period, Wells BR-5A and BR-5B will be re-entered to provide core samples into the chimney walls at selected levels, suggested here to be evenly spaced at quarter chimney heights. Wells BR-5A and BR-5B are tentatively located 40 ft outside the chimney on opposite sides. Analysis of the cores will provide data on the extent to which the treatment of the chimney has effectively retorted the shale beyond the chimney walls.

PHASE IV. FRACTURE ZONE TREATMENT

The purpose of Phase IV is to conduct an experimental in situ treatment of a selected sector of the fractured zone surrounding the chimney. The data will provide a basis for determining the technical and economic feasibility of extending in situ treatment beyond the chimney and for predicting the optimum spacing of multiple nuclear chimneys for a full-scale basin development program. The key questions to be answered are: To what extent does the fracture system remain open? What proportion of the shale oil potential can be recovered? To what distance? Is radioactivity a problem in the fracture zone?

As in Phase III the basic technical problems will not be identified until after the postshot evaluation; indeed, they may not be fully identified until after the treatment of the chimney rubble has been completed. While it is predicted that the oil shale will be fractured out as far as 460 ft by the nuclear explosion and expected that this fractured zone will exist at the outset of the chimney treatment, it is by no means certain that the fractured zone will still exist, in full or in part, at the time the treatment of the chimney is completed. It is entirely possible that the overburden pressure will have resulted in sufficient plastic flow to seal off a substantial portion of the fractured zone. The U.S. Bureau of Mines in Laramie is conducting a laboratory investigation of the effect of pressure on oil shale of various grades. The results of this effort are desirable to improve the capability to predict the behavior of the fractured zone under overburden pressure.

For the purpose of present planning, it is assumed that sufficient permeability will exist in at least a portion of the fractured zone and that it can be maintained sufficiently long to conduct a meaningful experiment. As in Phase III, the technical guidance committee will be faced with a choice of treatment method. The principal choices appear to be:

1. In situ combustion of residual coke with ignition over a segment of the chimney walls, possibly including further combustion of coke in the chimney rubble, with peripheral production wells.
2. In situ combustion commencing at peripheral injection wells with production from the same chimney wells as in Phase III.
3. Aboveground combustion of natural gas at high pressure and injection of combustion gases into the chimney or into peripheral injection wells.
4. Aboveground heating at high pressure of a mixture of gases in the absence of oxygen and injection either into the chimney or into a set of peripheral wells.

For the project planning purposes, it is assumed that:

1. The first of the technical approaches listed above is selected.
2. The air and recycle rates per ton of oil shale treated which were applicable to Phase III are also applicable to Phase IV.
3. The effects of the explosion are as predicted.
4. The oil shale grade data obtained from corehole No. 1 are applicable to the fractured zone.

It is proposed to confine the in situ treatment experiment to a 45° sector of the fractured zone and to investigate the efficacy of the treatment out to a radius of about 200 ft or 80 ft from the edge of the chimney. This sector of the fractured zone contains about one-fourth as much oil shale as does the chimney. Hence, treatment might be accomplished in about one year with about one-fourth the daily air rate required in Phase III.

The locations of additional wells for the fracture retorting experiment are shown in Fig. 8 and the detailed well specifications are shown in Table V. Figure 8 also

Table V. Well specifications for Phase IV.

	BR-4	BR-5	BR-10A BR-10B
Purpose	Injection	Production	Production
Distance from GZ	25 ft	160 ft	160 ft
Total depth	2800 ft	3400 ft	3400 ft
Minimum ID	12 in.	6 in.	6 in.
Drilling fluid	Mist	Mist	Mist
Casing size and depth	Existing	Existing	7-5/8 in. to 2300 ft
Tubing	Existing	From BR-6	From BR-7P and BR-9
Cement	To surface	To surface	To surface
Logs	None	None	γ-n Direction survey
Completion	Existing	Production tubing and liquid pump	Production tubing and liquid pump

	BR-11A BR-11B	BR-12A BR-12B	BR-13A BR-13B
Purpose	Temperature survey and coring	Production	Temperature survey and coring
Distance from GZ	140 ft	200 ft	180 ft
Total depth	3400 ft	3400 ft	3400 ft
Minimum ID	4-3/4 in.	6 in.	4-3/4 in.
Drilling fluid	Mist	Mist	Mist
Casing size and depth	5-1/2 in. to 2300 ft	7-5/8 in. to 2300 ft	5-1/2 in. to 2300 ft
Tubing	2-7/8 in.	2-7/8 in.	2-7/8 in.
Cement	To surface	To surface	To surface
Logs	γ-n Direction survey	γ-n Direction survey	γ-n Direction survey
Completion	Tubing for surveys	Production tubing and liquid pump	Tubing for surveys

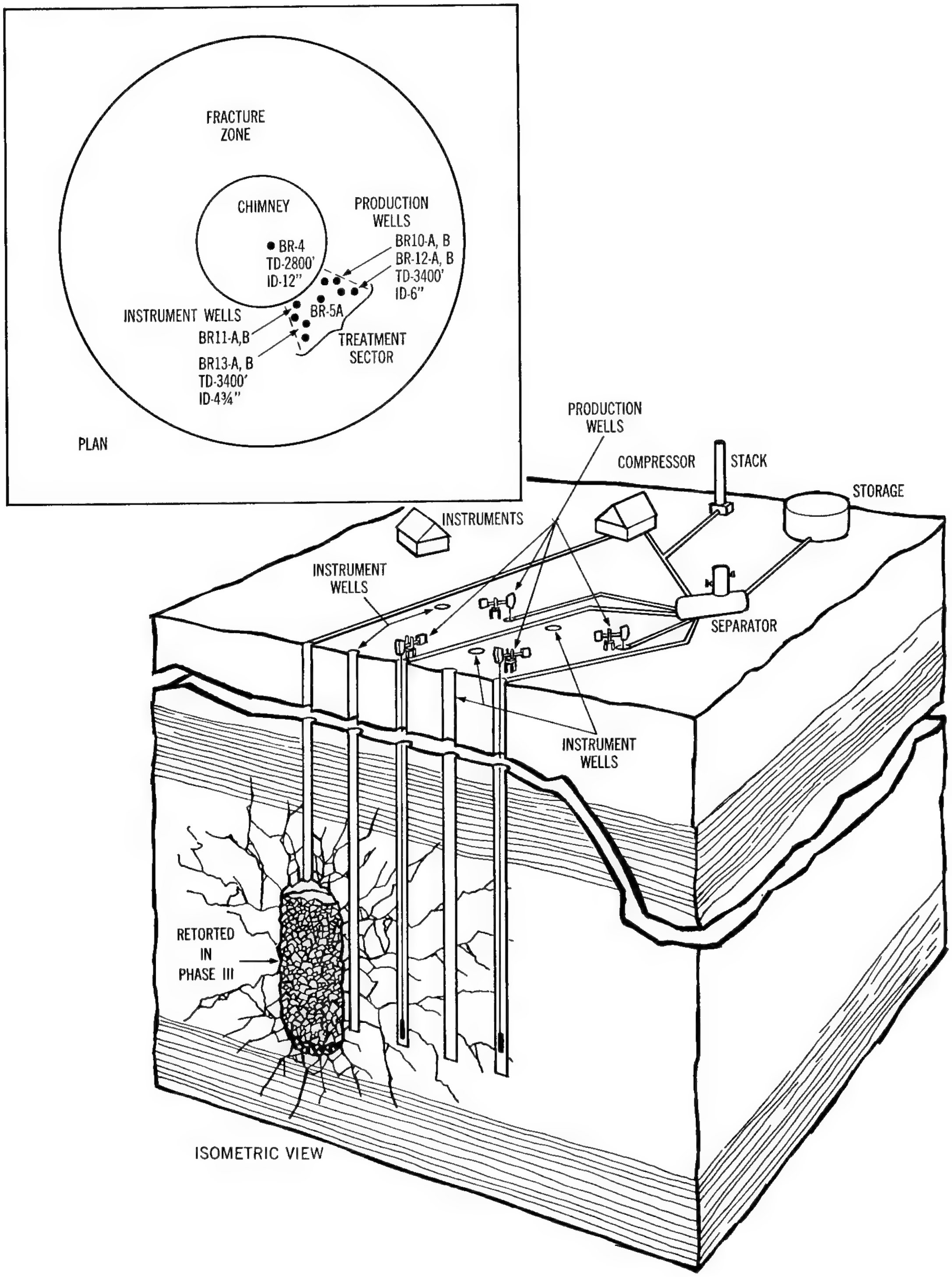


Fig. 8. Phase IV wells.

gives a schematic concept for the fracture zone treatment. The requirements are:

1. Hole BR-5 will be used as one of the first set of production wells. Prior to drilling the remainder of the set, pressure and flow tests will be conducted between BR-5 and one of the chimney injection wells, e. g. , BR-4, for use in predicting compressor and horsepower requirements.

2. New holes, BR-10A and BR-10B, will be drilled to a depth of 3400 ft at a distance of about 40 ft outside the wall of the chimney. The exact distance will depend upon the extent to which retorting into the chimney walls is revealed by analysis of cores taken from wells BR-5A and BR-5B. If it is found that insufficient permeability exists between the chimney and the production wells, it may be desirable to attempt horizontal fracturing with propping to achieve adequate permeability. Each hole will be cased to a depth of 2300 ft and cored opposite the chimney interval. Pressure and flow tests will be conducted in the same manner as with BR-5.

3. The three production wells, BR-5, BR-10A and BR-10B, will be equipped with 2-7/8 in. tubing and liquid lift equipment.

4. The compressor system installed in Phase III will be modified to provide the necessary pressure in the fractured zone and to overcome the necessary pressure drop at a flow rate of about 12 MMSCFD. In order to assure a capability for recycle of a fraction of the off-gas, it will be necessary to provide a combination system both to pressurize the added air to the system pressure at the injection well-heads and to offset the pressure drop of the recycle gas up to the production wellhead. The 6000 brake horsepower capability provided in Phase III should be adequate to provide the flow requirements indicated.

5. Two additional wells, BR-11A and BR-11B, will be drilled to a depth of 3400 ft about 20 ft outside the wall of the chimney. These holes will be drilled and cased to a minimum ID of 6 in. to a depth of about 2300 ft. A directional survey will be made of each hole after completion. During the course of the treatment of the fractured zone, these holes will be used for periodic wireline temperature surveys through the depth of the producing section of the oil shale formation. Periodic gas samples may be taken from selected intervals of these wells. At the conclusion of the treatment of the fractured zone, these holes can be used to provide core samples through the treated section of the oil shale.

6. Provided that the treatment of the fractured zone with production from wells BR-10A and BR-10B shows satisfactory results, two additional production wells, BR-12A and BR-12B, will be located and drilled to the same specifications as BR-10A and BR-10B, except that they will be spotted about 80 ft outside the chimney wall. The exact distance will depend upon the results of previous fracture studies and oil shale treatment. Limited fracture studies will be made in drilling these wells. These production wells will use tubing and liquid lift equipment transferred from other wells.

7. Two additional wells, BR-13A and BR-13B, will be drilled to the same specifications as BR-11A and BR-11B except that they will be spotted about 60 ft outside the

chimney wall. These wells will also be used for periodic temperature survey profiles as well as for recovery of gas samples during treatment of the sector beyond the first set of production wells. After completion of treatment of the sector, holes BR-13A and BR-13B can be used to recover cores in the treated zone of the formation.

8. No additional above-ground storage requirements are envisaged for either oil or water during Phase IV.
9. During the treatment of the fracture zone, periodic temperature profiles will be taken through the wells provided for this purpose. At the surface, continuous measurements of the important process parameters will be made (ambient flow rates, temperature and pressure). Periodic or continuous sampling will be made of the composition of the gaseous effluent. Gas samples will be analyzed for chemical composition and radioactivity. Periodic measurement will be made of the volumes and densities of oil and water samples recovered. The radioactive contaminants of the liquid products will be continuously monitored. The composition of the saline constituents of the water fractions will be periodically determined.
10. At the conclusion of Phase IV and in the absence of any new experimental requirements, the aboveground process equipment will be disposed of and the surface of the land will be returned to substantially the same condition in which it was at the beginning of the experiment.

SUPPLEMENTAL RESEARCH

PHASE I AND PHASE II

Explosive Performance – A limited number of diagnostic measurements of the energy yield and other performance characteristics of the nuclear explosive will be required as a part of the Bronco experiment. These measurements will be conducted at shot time, with the exception of the analysis of melt samples recovered in postshot drilling.

Rock Properties – Samples of preshot core from the vicinity of the detonation point will be subjected to laboratory tests to determine their radioactivity, chemical composition, and the following physical properties:

1. Hydrostatic compressibility up to 40 kilobars.
2. Triaxial tests at various confining pressures.
3. Tensile strength.
4. Hugoniot elastic limit.
5. High-pressure Hugoniot equation of state.
6. Sonic velocity.

These data will be used as input for computer calculations of the shock wave,

cavity growth, fracturing, and collapse leading to chimney formation. Core samples from postshot holes will be analyzed for radioactivity and examined in the laboratory for permanent physical changes resulting from the explosion.

Gas Sampling — Samples of gas will be taken in several postshot holes to determine the extent to which radioactivity has penetrated the formation. These samples will be taken with downhole bottles on a wire line or drawn to the surface from packed-off intervals through tubing. The gas will be analyzed for chemical composition and radioactive species. This information will be helpful in evaluating the fracturing caused by the explosion, leading towards eventually establishing the fracturing mechanism.

Dynamic Earth Motion — Holes BR-3 and BR-E will be fitted with peak-pressure gauges, stress history transducers, and shock velocity instruments. Data from these instruments will be useful in checking the accuracy of computer code predictions of shock wave history and cavity growth.

Ground Surface Motion — Accelerometers and velocity gauges will be used to measure ground surface motion within a few miles of surface zero. These data will be used in establishing minimum safe distances for equipment and facilities for subsequent explosions in the same vicinity.

Other Theoretical Work — Computer predictions will be made of the ground surface motion, the seismic wave, and the possible interaction of the chimney with overlying aquifers. Computer computations related to recovery of oil from the chimney may also be made, in connection with Phase III.

PHASE III AND PHASE IV

Thermodynamic and Physical Properties of Oil Shale — In situ retorting research studies at the Bureau of Mines Laramie Petroleum Research Center have been designed to provide information needed as a basis for the development of efficient methods for recovering shale oil from oil shale broken by underground nuclear explosions. Measurements have been made of the following thermodynamic properties: specific heat, heat requirements for retorting, thermal decomposition rates of oil-shale carbonates, thermal conductivity, and thermal diffusivity. Research has also been directed toward investigating the physical properties of oil shale, including the compressive strength of raw, retorted, and burned shales. The work is continuing.

Laramie 10-Ton Retort — A superior recovery technique must insure efficient heat utilization as well as the conversion of an optimum amount of the organic matter to a liquid product. The present 10-ton retort experiment is designed to investigate the retorting of ungraded oil shale under conditions similar to those expected in a nuclear chimney. Retorting studies to data have been made on mine run shale charges containing pieces as large as 20 in. in two dimensions. The third dimension has varied from several inches

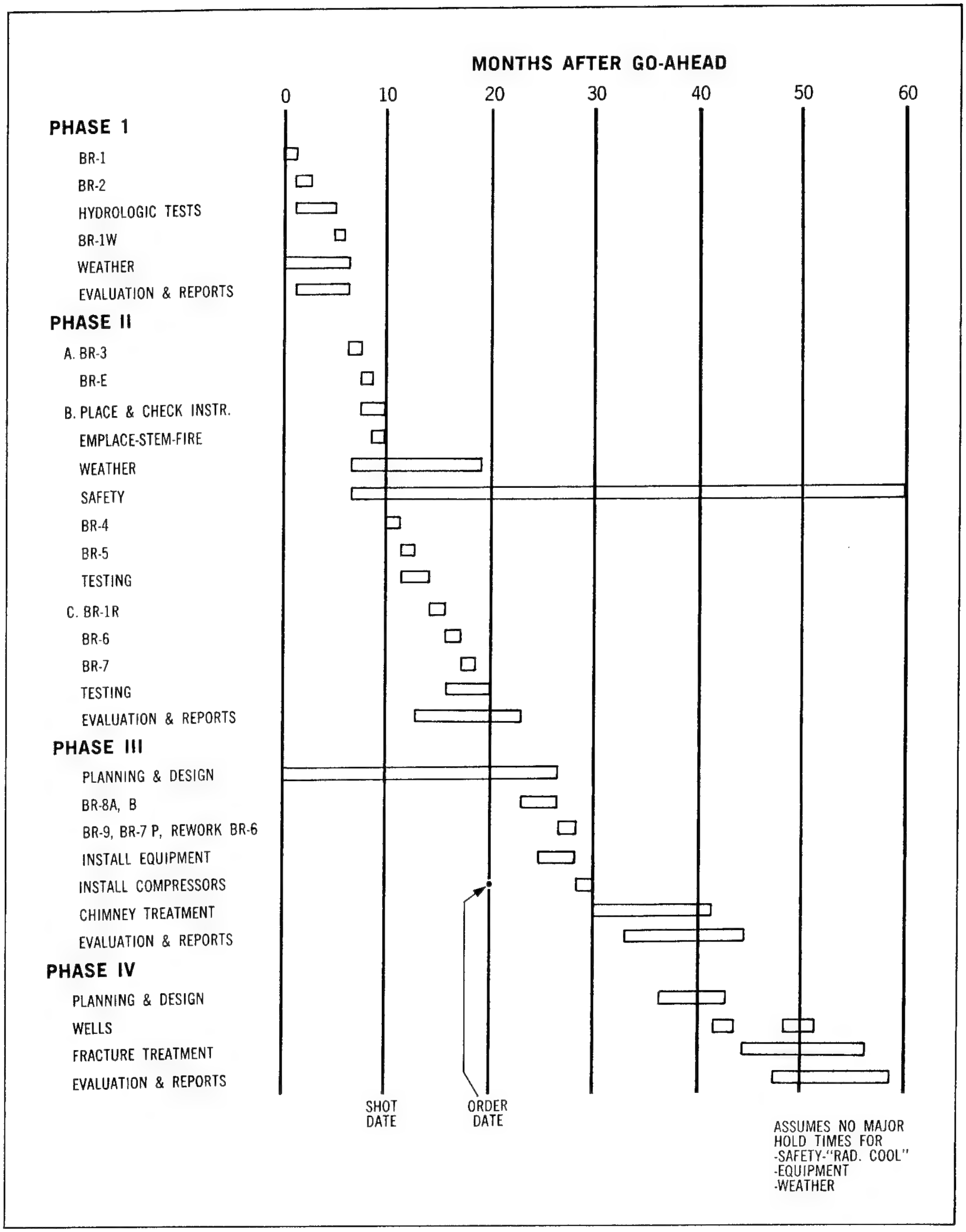
to 3 or 4 ft. Yields as high as 80% of Fischer assay have been achieved.

Carbon Residue Studies — Another current study will yield information on the maximum amount of heat obtainable by burning the carbonaceous residue remaining on spent shale. Results of this study should show whether a major portion of the heat required for retorting oil shale underground can be obtained by burning the organic residue remaining in the shale after retorting, or whether the heat should be generated by burning some of the product gas.

Laramie 150-Ton Retort — A new retorting experiment, larger than the present 10-ton operation, is proposed. The retorting characteristics of ungraded shale containing pieces as large as 4 ft in two dimensions will be determined. It is proposed that this experiment be conducted on shale charges of 100-150 tons, using a retorting vessel 12 ft in diameter and 45 ft high. Temperature and gas composition as functions of time and position in the bed will be recorded. Provision will be made for varying the air rate from 10,000 to 15,000 scf/ton and the ratio of recycle gas to air from 0 to 1.5. Retorting rates will be varied but will probably average about 2 ft/day (5 $lb/hr/ft^2$ of retort cross section). It is proposed to operate the equipment at slightly elevated pressures.

From data taken in the course of retorting runs, and from careful examination of the contents of the retort at the conclusion of each run, some insight into the question of combustion front stability will be gained.

Oil Shale Crushing Studies — The crushing tendencies of various grades of oil shale when subjected to retorting conditions such as might be encountered during the retorting of the rubble column of a nuclear chimney are currently being investigated. The equipment used for this work consists of an externally heated cylindrical vessel having a capacity of approximately 150 lb of shale. Provision is made for compressing the bed by loading with a hydraulically-operated piston. Pressures of up to 500 psi, equivalent to a bed depth of approximately 1,000 ft, can be applied. Data will be indicative of the ability of various grades of shale to resist crushing and attendant reduction of bed permeability during retorting. Crushing studies will be made at subretorting temperatures as well as at retorting temperatures, and on retorted and burned shales as well as on raw shale.



Estimated time schedule for Project Broncho.

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